Application of Geological Data for the Long-Term Safety Evaluation of the Nuclear Waste Disposal Systems

Laverov, N.P., Velichkin, V.I., Petrov, V.A., Pek, A.A., Omelianenko, B.I.
Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry (IGEM),
Russian Academy of Sciences
vlad@HYPERLINKigem.ru

ABSTRACT

Methodology for the acquisition of geological data required for the evaluation and provision of long-term safety of nuclear waste underground disposal (storage) systems is considered on the basis of the conceptual approach to the closing stage of radioactive waste (RW) management, which envisages fractionating of liquid high-level wastes (HLW) with the separation of fractions containing radionuclides with different half-life.

INTRODUCTION

In view of large volumes of nuclear materials accumulated in the Russian Federation and the necessity for harmonization of their management practice (Egorov, 1997) the trend is emerging towards the development of a new approach to the problems of the closing stage of radioactive waste (RW) management, which envisages their fractionating and separate disposal. The main idea of this approach is in the disposal of short-lived low-intermediate level RW (LLW-ILW) to shallow repositories, the burial of intermediate-lived heat-emitting high-level wastes (HLW) in the repositories located at depths ranging from 0.5 to 1.0 km, and the disposal of long-lived radionuclides belonging to the HLW actinide fraction to the repositories located at depths >1.0 km from the surface (Laverov et al., 1998, 2000).

Conditioned ***short-lived*** low-intermediate level RW, which must be sealed for a period of at most 300 – 500 years, according to the existing practice are disposed to the shallow reinforced concrete repositories in most cases located at the territory of sanitary protection zones (SPZ) of enterprises generating radioactive wastes (Melnikov et al., 1994).

At this stage main importance is attached to the provision of safe disposal of solidified ***intermediate- and long-lived*** RW. In this context, two novel pilot technologies for the preparation of these wastes for the disposal present a certain interest as follows:

- HLW fractionating and separation of actinide, cesium-strontium, rare-earth and palladium groups (Dzekun et al., 1996);
- Synthesis of highly-resistant Ca-Ti-Zr-containing mineral matrices of high isomorphic capacity for long-term confinement of radionuclides of the actinide group (Laverov et al., 1997).

The solidified HLW fraction containing ***intermediate-lived*** highly toxic and heat-emitting Cs, Sr and other radionuclides with a similar life-time must be separated from the ecosphere for a period, which will not exceed 1,000 years. However, since Cs and Sr present particular biological hazard, the systems for their disposal must be furnished with protective barriers of extremely high reliability. The realization of this safety condition can be provided through the construction of repositories for Cs-Sr-containing HLW at 0.5 – 1.0 km depths within the boundaries of undisturbed blocks formed by the rocks with efficient protective characteristics. Obviously, it is feasible to build such repositories in immediate proximity to the radiochemical operations of the MINATOM (PO Mayak, Ozersk; MCC, Zheleznogorsk, etc.), where the main volumes of HLW resulting from the production of nuclear weapon materials are stored, and where HLW resulting from spent nuclear fuel (SNF) reprocessing are now being accumulated or will be accumulated in the future.

With the construction of repositories for ***long-lived*** radio nuclides belonging to the HLW actinide fraction the reliability and safety of disposed radioactive material separation from the human habitat must be guaranteed for many millennia. It is feasible to build such repositories furnished with protective engineered barriers at depths of at least 1.0 km from the modern surface and to set them in geological blocks formed by the rocks with efficient sealing properties and characterized by the absence of meaningful seismotectonic activity in the preceding geological epochs. Thus, long-lived radionuclides will be sealed for the required period, and the risk of the loss of impermeability of repositories and the release of harmful concentrations of radioisotopes in the ecosphere will be minimized.

Since the share of long-lived radionuclides in the total volume of HLW is rather small, while the conditioned forms of these radioisotopes are characterized by low heat emission rates, high stability and they present no serious hazard in transportation, it was proposed (Laverov et al., 2000) to consider the feasibility of the construction in the Russian territory of one or two national underground repositories for HLW containing long-lived radionuclides. Geological blocks located within the boundaries of ancient shields and platforms, which are the most stable elements of the earth's crust, seem most promising for the purpose.

To the authors' view this approach to the problem of safe HLW separation from the human habitat has the following technical and economic advantages:

- Physical safety criteria for repositories of various HLW fractions can be elaborated, and on their basis individual systems of natural and engineered barriers, which are necessary and suitable for the reliable sealing of every fraction can be identified;
- With the introduction of HLW fractionation and, the resulting multifold reduction of the volume of wastes containing long-lived radionuclides and requiring long-term reliable conditions for their sealing the expenditures for HLW underground disposal will be sufficiently lower.

In this paper main attention is focused on the criteria for the selection of geological conditions providing for long-term safety of a repository system for intermediate- and long-lived HLW fractions.

DISCUSSION

For rational selection of geological conditions providing for the long-term safety of a repository system for intermediate- and long-lived HLW fractions in crystalline rock massifs it is necessary to identify the factors, which are critical for every such fraction. Main factors of the kind are presented in the Table 1 below:

Table 1. Main factors determining the long-term safety of the repository systems:

	Factor	*Intermediate-lived* (half-life < 30 years)	*Long-lived* (half-life > 30 years)
Far-field Environment:	Geomechanical stability of geological blocks	Relatively stable	Stable
	Hydrological conditions	Groundwater travel time: 400-500 years	Groundwater travel time: 5,000-10,000 years
	Hydrogeochemical conditions	Reductive-oxidative	Reductive
Near-field Environment:	Thermo-mechanical processes	Thermoweakening	None
	Transport mechanism	Thermoconvection flow	Diffusion, transfer of a colloid form is possible
Geologic Disposal Scheme:	Deep disposal containing an engineered barrier system	Shaft, borehole at depths of 0.5-1.0 km. Engineered barriers perform the principal protective function	Borehole, at depths > 1.0 km. Geological barrier performs the principal protective function

If the Geologic Disposal Scheme based on a multi-barrier protection system is chosen, it is necessary to take into account the fact that there is a continuous interference and interaction between an engineered structure (repository) and geological environment where it is located, i.e., they must be considered a single integral system, as is the convention in engineering geology. A rock massif is the element of this system, which is most difficult to investigate, as in the process of geological evolution its structure, characteristics and state were affected by numerous changes. As a result, the following peculiarities of a massif were formed: discontinuity (fracturing), heterogeneity, anisotropy of characteristics and natural stressed state. They are governed by specific principles at various hierarchical levels, and these principles differ from those governing the behaviour of construction materials. Therefore, for the evaluation of the long-term reliability of a repository it is necessary both to comprehensively investigate the structure, characteristics and state of the adjoining rock massif, and to identify the regularity, intensity and trends of geological processes. Thus, in the context of Site Selection and Site Characterization procedures it seems feasible to consider the identification of favourable geological conditions on a space and time scale.

Localizing in space is understood as a conventional procedure for the selection of a favourable formation of crystalline rocks from Regional (>> 1000 m), through Site (100-1000 m), Block (10-100 m) to Detailed (0-10 m) level (Gustafson et al., 1991). In this case, for every geometric scale it is the practice to develop an individual long-term plan of investigation of the geological environment including geomechanical, mineral and chemical, hydrogeological, hydrogeochemical, transport and other characteristics.

If the conception of fractionating and separate disposal of intermediate- and long-lived HLW fractions is taken as a basis, the procedure for the selection of a favourable geological formation and the system of geological and geophysical methods used for the purpose become more efficient. For instance, for the actinide group the disposal system in deep (up to 2.0 – 3.0 km depths) boreholes seems most preferable. Accordingly, the problems concerning the destructive effect of seismic processes on a repository or its rise to the surface resulting from erosion or global climate changes become less pressing. Therefore, the expenditures for geomechanical tests, geomorphological survey of the territory, etc., can be minimized.

As it was mentioned above, the variability and heterogeneity of the structure are the most important characteristics of the geological environment. Therefore, they must be taken into account both while choosing the sites potentially favourable for the construction of repositories, and while elaborating and implementing the programmes aimed at the detailed investigation of selected blocks, as well as in the evaluation of long-term safety of a disposal system. Evidently, the history of geological evolution of a geological formation is the most important factor determining the heterogeneity of its interior structure. Therefore, the reconstruction of the history of rock massifs, identification of their modern characteristics and conditions, as well as the prediction and estimation of options for the development of geological processes in the future, present the time scale that must be taken into account in the context of Site Selection, Site Characterization and Long-term Safety Evaluation procedures.

This assumption can be illustrated by the case of Preliminary Characterization performed on the territory of the PO Mayak in the South Urals, where it is planned to dispose solidified heat-emitting HLW containing intermediate-lived Cs, Sr radionuclide in the future. For this purpose use is made of geological, mineral-chemical, geomechanical, hydrogeological, hydrochemical and petrophysical data obtained on a regional and site basis. In the description of the processes the authors go from the assumption (McEwen et al., 1999) that the past processes are those, for which one may get palaeo-evidence from geological record, prevailing (current) processes are those, which one may be able to monitor, and future processes are those, which one has to predict/estimate based on the extrapolation of past and present data..

Geological Data

The geological structure of the territory of the PO Mayak is organized by the rocks of gneiss-amphibolite (PR3-PZ1), volcanogenic-sedimentary (S-D1) and carbonate-terrigenous (C1-2) complexes. More detailed research was undertaken into volcanogenic rocks, which form the main part of the SPZ territory. Geological investigations were aimed at the identification of geological blocks applicable for HLW underground disposal, and which nature of folded structure, tectonic disturbance and size are suitable for the construction of a repository.

A system of discontinuities was discovered in metavolcanite strata. They were formed in different deformational episodes of the geological environment. According to morphogenetic characteristics, time of origin (from more ancient to younger discontinuities) and scale, they were grouped by types as follows: 1) zones of deep fractures with silicification of rocks and the systems of contiguous quartz veins; 2) schistosity zones with cleavage; 3) mylonite sutures and brecciation zones with chlorite, chlorite-epidote-quartz cement; 4) numerous systems of fractures, as well as quartz-carbonate and carbonate veinlets (Velichkin et al., 1995). Linear schistosity zones, as well as mylonite sutures and brecciation zones are dominating intrablock structures. Rocks within the boundaries of these zones are characterized by high effective porosity and permeability, however the values of their elasticity and strength parameters are rather small (Petrov et al., 1998). The analysis of the set of discontinuities shows that within the boundaries of geological blocks of the basement major role in the spread of radionuclide contamination will belong to linear schistosity zones, mylonite sutures and breccciation zones, as well as to various systems of fractures. Since zones of faults were not suitable for HLW underground disposal they were not considered at all, while the blocks separated from each other by such zones were recommended for further investigation. The size (~ 1.5-2.0 _ 1.0-1.5 km) of blocks located within the SPZ territory of the PO Mayak is suitable for underground disposal of solidified HLW in 0.5 – 1.0 km boreholes (Velichkin et al., 1997).

The main objective of geomorphological research is the selection of geological blocks, which epeirogenic rising intensity in the period of intermediate-lived HLW potential hazard will not result in the repository removal to the erosion level and its eventual destruction. The research shows that the SPZ territory is located in the zone of the Uralian peneplain, which was affected by rising and erosion in the Neogene-Quarternary time. The assessment of neotectonic activity undertaken on the basis of the analysis of the absolute levels of occurrence of the Late Miocene surface of levelling shows that the amplitudes of Pliocene-Quarternary vertical movement ranged from a few to 10-15 m. (Kochkin et al., 1997). If such conditions remain, or even if the intensity of erosion grows by the order of magnitude, the HLW repository located at a depth of 0.5 – 1.0 km may be removed to the level of erosion by far beyond the expiration of the planned safety period.

Geomorphological research has resulted in the identification of a series of neoformed releif-modifying faults (lineaments) of the NE, NW and submeridional orientation, which either succeed to disjunctives of more ancient origin, or which are presented by flexures in sediments. For the quantitative analysis of modern movements along these lineaments it is necessary to perform geodetic tests such as high-accuracy re-running of levelling, triangulation, GPS, range measurements, etc.

Mineral-Chemical Data

Volcanogenic (S-D1) andesite-basalt and basalt rocks occur as lava, pyroclastic and sedimentary-pyroclastic diversity. The transformation of the entire strata of original volcanites in the process of regional green-schist metamorphism has determined higher homogeneity of their petrochemical characteristics. The subsequent low-temperature hydrothermal-metasomatic transformations most clearly shown in the zones of dislocations have resulted in the replacement of original minerals (pyroxene, Ca-Na plagioclase, amphibole) with the aggregates of albite, actinolite, epidote, chlorite, prehnite, quartz, sericite, carbonate and haematite (Petrov and Poluektov, 1999).

It was discovered that discontinuities differ substantially in the composition of mineral filling. Zones of large faults occur with intensive silicification of rocks and the systems of contiguous quartz veins. Mineral filling of schistosity zones occurs as albite, sericite, chlorite, epidote and tremolite. Mylonite sutures and brecciation zones are filled mainly with chlorite, chlorite-epidote-quartz aggregates and numerous carbonate, quartz-carbonate and quartz-epidote veinlets. Mineral filling of fractures includes the following: quartz, epidote, chlorite, quartz-epidote and quartz-carbonate aggregates. Since particular radionuclides are sorbed by mineral aggregates of a certain composition (for instance, Cs⇒ biotite + chlorite, Sr⇒ K-feldspar + carbonates + epidote) (Solodov et al., 1986), the obtained data must be taken into account for the identification of transport characteristics of discontinuities.

Besides, experimental data shows that at a temperature of 150–_ and P_{H20}=1 kbar pressure the original minerals (Ca-Na plagioclase, pyroxene, olivine) of the solid volcanites matrix are replaced by the minerals with high sorption capacity, such as, epidote, chlorite, hydromica, mixed-layered and argillaceous minerals. Positive volumetric effect of substitution reactions determines the colmatage of pore-and-fracture space that generally results in the reduction of the permeability of rocks. Thus, there is an actual opportunity of considering mineral and chemical data not only for the identification of favourable types of rocks, but also for the prediction of coupled thermal and hydrological processes in the near-field of a heat-emitting HLW repository

Geomechanical Data

The analysis of the results of structural-geological and tectonophysical investigations showed that folded structures and discontinuities of the territory under consideration had been formed during three deformational episodes of the geological environment, namely, Hercynian, Mesozoic and Cainozoic episodes. During the Hercynian episode folds of various sizes with linear zones schistosity accompanied by cleavage and regional thrust faults were formed in conditions of transpression, regional metamorphism of the volcanogenic-sedimentation strata and green-schist facies. At the final stages of deformation, when stresses were higher than the compression strength of rocks, mylonite sutures were formed and the development of the principal fracture systems was initiated. At the stage of main movements in the Mesozoic episode the principal $\sigma 1$ and $\sigma 3$ axes were oriented subhorizontally. It is the evidence of the strike-slip tectonic regime. In such conditions there were formed main brecciation zones and numerous fracture systems filled with heterogeneous hydrothermal mineralization. During the Cainozoic deformational episode associated with the regional sublatitudinal compression accompanied by the decay of hydrothermal activity there emerged a system of neoformed relief-modifying faults and individual fractured zones. As it was shown above, the lineaments of the NE, NW and submeridional orientation either succeeded to disjunctives of more ancient origin or they are presented by flexures in sediments.

The modern stressed-strained state of the geological environment on a regional scale is determined by the dynamic effect of the Ufimsky projection of the Russian platform. It is demonstrated as a sublatitudinal comression of rocks. The absolute values of stress deviator component range from 20 to 50 MPa at 100 – 300 m depths from the surface. These conditions have remained in the Urals at least since the Holocene period (Aleinikov et al., 1988).

This deformation pattern is reflected in the modern stressed-strained state of the geological environment of the PO Mayak territory. The reconstruction of the stress regime of the latest Cainozoic movements on the basis of the analysis of fault slip data sets shows that slip dislocations are typical of the NE and NW oriented faults, while the faults of submeridional (uralian) orientation are affected predominantly by reverse and reverse-slip movements. However, sublatitudinal faults demonstrate the highest dynamic instability in the local field of stresses. Tension dislocations are predominant in these zones. This may explain the fact that sublatitudinal fractures are more hydraulically active than those of some other orientation. It is also worthy of mentioning that the asimuthal distribution of strains within the blocks, with background seismic vibrations identified during the relaxation process monitoring (Adushkin et al., 1997) is a good evidence of the fact that the modern deformation pattern has succeeded to the Cainozoic pattern. Apparently, for more detailed identification of components (orientation of principal axes, anizotropy, etc.) of the modern field of stresses it is necessary to perform stress measurements with a help of such methods as hydraulic fracturing and/or overcoring.

According to the existing seismic zoning of the Urals the neighbouring areas of the territory under investigation are prone to earthquakes with an intensity of 6 – 7 and a magnitude of 4-5 (Kononenko et al., 1990). The faults of ancient origin, along which the displace of the Quarternary sediments are found, can be considered the most probable zones of the relaxation of modern stresses. Since seismodeformational processes may disturb the impermeability of a repository and change the dynamics and physical-chemical parameters of ground waters, these seismically hazardous structures are not included in the blocks recommended for HLW underground disposal.

At the same time, it is necessary to take into account the results of previous studies (Starostin et al., 1995). They show that the wrapping of a viscous-rigid massif (diabases, basalts, gabbro, dunites, etc.) in elasto-plastic rock complexes (terrigenous carbonate layers and bands of slates) presents the most favourable geomechanical situation. In this case (all other factors being equal), in the process of eventual deformations the chosen massif will avoid substantial deformational transformations, rearrangement of the geological structure and variation of hydrodynamic conditions, as it will be protected by plastic strata neutralizing abnormal stresses. An HLW steel container enclosed in backfill is an engineered analogue of this geomechanical situation. With reference to underground construction it is necessary to perform the analysis of geomechanical characteristics of volcanogenic-sedimentary rocks on the basis of indices indicated in various classifications (Bieniawski, 1973; Barton et al., 1974) and models (_undall, 1971).

Hydrogeological and Hydrochemical Data

Geological environment is the most important natural barrier preventing the release of radionuclides from the disposal (repository) zone to the ecosphere, however, the radionuclide transport by groundwater flows is the main mechanism of their transfer. Therefore, the safety of RW underground disposal to a great extent depends on both geological and hydrogeological conditions, which determine the structure and the velocity of groundwater flows in the area including the zone of the underground repository location. With regard to hydrogeological conditions the maximizing of the groundwater travel time from the repository zone to the biosphere is the most natural safety criteria for underground disposal.(Chapman and McKinley, 1987; The Scientific..., 1995). In this case, it is important to take into account both the configuration of the groundwater line of flow (primarily, its length) and the velocity of flow. The qualitative analysis of hydrogeological conditions on the basis of this approach has helped to identify (The Scientific..., 1995) several rather general types of geological environment, which can be chosen for the construction of underground RW repositories. The geological environment of the PO Mayak territory most closely resembles the “c” type, i.e., basement rocks under sedimentary cover, however the actual thickness of sediments is insignificant.

The only aquifer occurs in rock of the eluvial-sedimentary complex irregularly overlapping the rock basement (Solodov and Zotov, 1995). With the available average values of n 10^{-4} mD permeability and 0.4 % effective porosity of the solid matrix of rocks the rate of filtration, at a regional pressure gradient of 1.5 g/cm^3, will amount to nearly $5 \cdot 10^{-5}$ m/year (Petrov et al., 1998). Therefore, linear zones of the tectonic disintegration of rocks will form the most probable media for the transport of groundwaters at the depth of HLW repository location. For the prevention of groundwater thermoconvection it will be necessary to eliminate the presence of hydraulically active discontinuities in the gradient temperature field of the repository. While choosing these structures one should give due account to geological and geomechanical data, since in the modern geohydrodeformation field the tension and slip faults oriented at an acute angle to the axis of maximal compression ($\sigma 1$) will have the highest filtration capacity.

In most cases head gradients determined by the relief of the surface serve the principal reason of groundwater migration. The general recommendation on the minimization of the effect of this factor is in the selection of the site with an utmost even local relief. With the current relative invariability of modern geological, hydrogeological and other conditions affecting the migration of radionuclides in the underground hydrosphere the numerical modelling of the scenarios of the evolution of the underground disposal system can be performed (Malkovsky et al., 1997).

For the modelling of long-term consequences of underground disposal the presence of a deep-seated heat source and/or different thermal conductivity of various rocks must be taken into account, since it may result in the substantial inclination of isothermal lines towards the horizontal plane. In this case, free-convection flow propagates in any circumstances, and for the modelling of contaminant migration from the repository zone some adequate approaches must be found to the problem of free thermal convection resulting from heat emission of the buried wastes and non-horizontal position of geoisothermal lines, as well as to that of free concentration convection stemming from the diversity of the composition and therefore of the density of groundwaters.

Hydrochemical research was aimed at the analysis of the modern composition and physical-chemical characteristics of underground waters for the eventual identification of such conditions, which will make difficult the migration of radionuclides from the HLW repository, if its impermeability is disturbed. The available data (Solodov, Zotov, 1995) shows that groundwaters of the PO Mayak territory are submineralized, with carbon dioxide, sodium and calcium as main components. It is expected that at depths of 0.5 – 1.0 km groundwaters are alkalescent, nearly neutral with reducing characteristics, and this will make difficult the transport of radionuclides over long distances. To test this hypothesis it seems feasible to use the method of hydrogeochemical logging of non-cased wells with an application of a multichannel hydrogeochemical probe integrated in the data acquisition, processing and storage system. This device was designed by the experts of the IGEM RAS.

Petrophysical Data

The combination of petrographic (optical) investigation of textures and laboratory studying of physical-mechanical characteristics is helpful for the identification of the nature and intensity of deformational tramsformations of rocks. Changing of original volcanites of the PO Mayak territory in the process of greenschist metamorphism has determined the formation of the environment with relatively homogeneous texture characteristics and petrophysical properties. It is clearly demonstrated in the areas found outside the zones of dislocations. Non-disturbed and non-weathered rocks are characterized by high density, elasticity and strength, as well as by minimal values of effective porosity and permeability (n 10^{-4} mD). Major variations of petrophysical parameters and mineral-chemical characteristics are associated with the zones of dislocations. There, the original minerals (pyroxene, Ca-Na plagioclase, amphibole) to a great extent are replaced by albite, actinolite, epidote, chlorite, prehnite, sericite and carbonate, with a wide spread of blastomylonitic, cataclastic and brecciation textures. There, rocks are characterized by low elasticity and mechanical resistance, however higher values of permeability. Thus, but for such discontinuities, as linear schistosity zones, mylonite sutures, brecciation and contiguous fracture zones, the studied rocks are considered favourable for the construction of an underground HLW repository by their petrophysical characteristics.

However, the presence of these heterogeneities allows on the one hand, with a great deal of caution to apply the results of laboratory test to the entire massif, while on the other hand, it helps to use a more reasonable approach to the quantitative analysis of physical-mechanical characteristics of rocks *in situ*. For this purpose it is necessary to use a system of seismoacoustic, electrometric, gravimetric and other methods of engineering geophysics. It is even more important, as the expected underground disposal of heat-emitting HLW requires more detailed investigation and assessment of coupled thermo-hydro-mechanical processes. Tentative results of laboratory tests allow only the following statement: with P-T parameters simulating the conditions of the HLW repository near-field environment (T=80-200^{O}C, P_{fluid}=130-300 bar) in metavolcanites, on the one hand, the integrity of the original system of fracture and pore channels is disturbed, however, on the other hand, neoformed microfractures may be filled with the minerals with a high sorption capacity for Cs and Sr, such as epidote, chlorite and carbonate.

CONCLUSIONS

Thus, the case study of the PO Mayak territory demonstrates the methodology for the investigation of the geological environment, which is of potential importance for the construction of a HLW repository. The performed research can be considered the stage of Preliminary Characterization on a regional and site basis with some elements of Preliminary Predictions. The obtained geological, mineral-chemical, geomechanical, hydrogeological, hydrochemical and petrophysical data can be considered a foundation for the work aimed at the Detailed Characterization of the composition, characteristics and state of individual blocks with the eventual demonstration of the suitable geological and hydrogeological conditions providing for Long-term Safety of a borehole-type disposal system (Table 2). Evidently, the final decision on the acceptability of these conditions for underground disposal of heat-emitting HLW can be taken only according to the results obtained in the underground research laboratory (URL).

Methodology of geological investigation of the territory of the PO Mayak can be offered for application with due account for individual features of the structure, characteristics and conditions of rock massifs and other objects located in the Krasnoyarsk Region and Kola Peninsula. By present, work on Site Selection and Preliminary Characterization on a regional and site basis has been completed already. Today, it is necessary to turn to Detailed Characterization. This work can be performed with due consideration of the accumulated experience and in close co-operation with the respective establishments, as well as with the support of the international community. In this context the proposed approach to the problems of the closing stage of RW management, which envisages their fractionating and separate underground disposal, might shorten the time and minimize the expenditures for research, design, construction and commissioning of HLW repositories.

Table 2. Summary of safety-relevant data:

Data	Positive Factors	Negative Factors	Removal of uncertainties
Geological	• Low regional vertical motions (±1mm/year) • Low seismicity • Spatial extention of the metavolcanic strata (S-D1)	• Intrablock faults (mylonite, breccia) and fracture sets • Neoformed lineaments • Argayaschsky reverse fault	• Deep horizons: Coring and geophysical investigations • Modern movements: Geodetic measurements (re-running of levelling, triangulation, GPS, etc.)
Geomechanical	• Relatively stable stress regime from at least Holocene (regional scale)	• Tension dislocations of intrablock sublatitudinal faults • Intrablock fault failure zones extend up to 3 m • Zones and packets of disintegrated rocks and clay	• Geomechanical characteristics: Rock Mass Classification Systems • Modern stress conditions: In-situ stress measurements (hydraulic fracturing and/or overcoring)
Hydrogeological and Hydro-chemical	• Small vertical and horizontal regional flow velocity values (~10^{-5} m/year) • Permeability (excluding fault zones) ~ 10^{-15} m^2 • Reductive conditions at depths > 500 m	• Hydraulic activity of intrablock faults • Thermoconvection flow (possible)	• Hydraulic gradient: In-situ hydraulic measurements • Transport properties: Fracture system flow (packers) and migration (trasser) tests • Mass balance calculations, Hydrodynamic modelling
Mineral-Chemical and Petrophysical	• Intrablock fault infill by the minerals with high sorption capacity • Rock matrix: high density and strength, low porosity and permeability values • Positive volumetric effect and forming of minerals with high sorption capacity	• Blastomylonitic, cataclastic and brecciated textures • Destruction of initial pore space due to thermal weakening	• In-situ petrophysical conditions: Seismic and radar tomography, etc. • Near-field conditions: Detailed characterisation of coupled thermo-hydro-mechanical processes (URL is needed)

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